Coastal hydrosystem responses to sea level rise

Terry Hume and Deirdre Hart

Dawn at Oneroa Beach
Waiheke Island (Photo: Terry Hume)

Introduction

Coastal hydrosystems comprise a diverse set of environments at the interface of terrestrial and marine systems that span a gradient from near-coast freshwater lakes and wetlands though to fully marine systems. Common terms for these features include: saltmarsh, lagoon, hapua, river mouth, estuary, harbour, sound, fjord, and bay. Hume et al. (2016) classify over 500 individual New Zealand (NZ) coastal hydrosystems, providing data on their bio-physical characteristics, as well as on their services, values and uses. The classification provides a 6-level hierarchy, with each level describing the dominant cause of variation in hydrosystem character at an associated spatial scale (see Table 1). It postulates that climate, geology, ocean, river and catchment factors broadly determine the physical and biological character of coastal hydrosystems. For our climate change and sea level rise (SLR) response analyses we focus on the Geomorphic Class (Level III), which sees hydrosystems defined as single units or complex systems amongst 11 distinct classes (see Table 1 and Images 1 to 11), some with subclasses (denoted by letters A to E). Since these hydrosystems are subject to water, sediment and energy inputs from both land and sea, they are particularly susceptible to both human-induced and natural environment changes. Through a physical process lens, this article discusses the potential responses of different types of coastal hydrosystem to changing climate and SLR, including a range of coastal management implications.

Potential effects of climate change and SLR on coastal hydrosystems

Projections of SLR for the NZ region suggest that by 2120 absolute mean sea levels will be between 0.55 and 1.36 m above mean 1986 to 2005 levels (MFE 2017). The actual rise largely depends on our global greenhouse emissions pathway and the non-linear response of the polar ice sheets to warming above a tipping point. Up to 2060 there is more certainty in projections, with a NZ region absolute mean SLR expected to total between 0.3 and 0.5 m. Locally and regionally relative SLR will be offset or enhanced to some degree by long term and event based vertical land movements (MFE 2017, pp. 82-86; and see 'Future sea level rise around New Zealand's dynamic coastline', p11). In addition to SLR, climate change is predicted to result in an increase in the frequency of occurrence and intensification of storms, affect long term through to inter-annual timescale sea level variations, cause changes in sediment supply, and alter the levels of incident wave energy at the coast. As a result, coastal systems of many kinds are expected to experience more frequent, widespread and intense inundation and erosion relative to the present day (Oppenheimer et al., 2019).

Effects of SLR and climate change will likely vary between hydrosystem classes, through the interaction of key factors that distinguish the form and function of coastal hydrosystems. These factors include: basin morphometry (shape and depth), hydrodynamic forcing from river inputs (flows, and volume of water and sediment), ocean forcings (tidal reach and prism, wave climate), and the longshore transport of sediment (see Table 1). For instance, shallow basins with extensive intertidal areas flanked by low lying plains will be more affected by SLR than deeper largely subtidal systems with steep sided shores. SLR will see intertidal areas deepen and more frequent, widespread and intense inundation of low lying coastal margins. Where this is prevented by rising ground or stopbanks the intertidal area will be reduced by coastal squeeze, disproportionately affecting upper tidal zones. Consequent changes in drainage

Level	Spatial scale (km^2)	Controlling factors	Potential changes in controlling factors with CC & SLR
I Global Temperate Australasian Realm	Macro 10^6 - 10^4	climate, landmass, watermass	• Warmer climate on average, with increased climatic extremes and more intense events. • Landmass: no change at this scale. • Increased ocean wave energy, temperatures and acidity with changes in storminess and ocean temperatures, higher absolute sea levels.
II Hydrosystem Palustrine, lacustrine, riverine, estuarine, marine	10^3 Meso 10^1	landform, water regime	• Landform: changes in basin morphometry (shape and depth) possible. • Water regime: increases in wetter weather in western NZ and southern SI, increase in frequency of heavy precipitation events and flooding throughout NZ, increase in intensity of ex-tropical cyclone events, longer dry spells in the north of the NI and east of both islands. • Shifts in the balance between river, tide and wave processes could trigger potential shifts between hydrosystem level II types for a limited number of systems (e.g. waituna - lacustrine to estuarine to marine).
III Geomorphic Class 11 classes (damp sand plain lake; waituna-type lagoon; hāpua-type lagoon; beach stream; freshwater river mouth; tidal river mouth; tidal lagoon; shallow drowned valley; deep drowned valley; fjord; coastal embayment), with 21 subclasses		geomorphology, hydrodynamics/ hydrology	• Geomorphology: changes in hydrosystem bathymetry and shorelines with (resulting from?) increases in coastal inundation extents & depths, changes in rates and patterns of sedimentation and longshore transport. • Hydrodynamics: altered balance between wave/tide /river influences, varying between hydrosystem class and around the country due to changes in the balance between hydrodynamic forcing (with changing river flows, volume and sediment transport) and ocean forcing (tide range and prism, wave climate) and longshore transport of sediment, with consequent changes in mixing, flushing, tidal exchange, saline intrusion. • Potential switching between classes for a limited number of hydrosystems, changes between some subclasses more common.
IV Tidal Regime Subtidal, intertidal, supratidal		inundation by the tide	• Inundation by the tide: zones elevated and translated landward via movement of groundwater and surface water with rising sea levels, where topography and development allow.
V Structural Class Vegetation, substrate, water structure	1 Micro 0.1	bio-, geo- and hydro-components	• Bio-, geo- and hydro-components: ecological succession and/or 'ecosystem squeeze' processes depending on supratidal topography, sediment supply and type, and anthropogenic modification of shore and invasive species.
VI Composition Dominant biota, substrate and water types		a mixture of the above	• A mixture of the above: gradual to extreme shifts in dominant biota with ecological successions, ecosystem squeeze and, for some systems and locations, hydrosystem class and subclass switches.

Table 1. NZ coastal hydrosystems classification hierarchy of levels, and sensitivity of hierarchical controlling factors to the effects of climate changes and sea level rise.

patterns and water table elevations will displace freshwater aquifers, rendering some current freshwater sources unusable, and rivers may experience greater saline intrusion, increased backwater effects and increased hinterland inundation. Climate changes will cause changes to freshwater inputs as rainfall and runoff patterns change, altering balances between river and tide forcing. More frequent floods or droughts could deliver greater or lesser catchment sediment volumes to coasts, though basin shallowing from this may be offset by SLR.

NZ coastal hydrosystem classes and response to SLR and climate change

This section describes the distinguishing characteristics of each NZ coastal hydrosystem geomorphic class (see Images 1 to 11) and the potential SLR and climate changes responses (attributions for the images used are presented at the end of this section). We refer readers to 'Estuaries and lowland brackish habitats' (p55) and to 'The response of sandy coastal systems to changes associated with sea level rise' (p25) for more information regarding estuarine and coastal embayment 'pocket beach' systems, respectively.

1. Damp sand plain lakes

Damp sand plain lakes are palustrine hydrosystems occurring as small, shallow (1 to 2 m deep), fresh/brackish water bodies, that are never connected to the sea. They are located in depressions between sand dune ridges and often associated with vegetated wetland areas. They form where the wind has removed sand to create shallow depressions down to about the level of the water table. They receive freshwater inputs from rain and groundwater, with salt spray and evaporation making them mainly brackish. They are variable in planform, ephemeral in space and time, and can dry out in drought conditions. Examples occur at: Parengarenga Spit (Northland) and Farewell Spit (Golden Bay), and on low lying coastal plains at the Kaipara Heads and Manukau Heads (Auckland).

For damp sand plain lakes, the overall responses to climate changes and SLR are likely to result in a range of outcomes between complete losses of some systems to minor water balance effects in others.

Rising sea level and storm tides will inundate these features in situations where the sand plains are low lying, unless inundation is offset by plain accretion through aeolian processes. As a result, damp sand plain habitat will be lost as inundation advances inland while a warming climate may see the lakes drying out more frequently, with consequent shifts in their biota. In some places, rising groundwater levels could lead to lake formation in previously dry depressions or to the deepening of lakes.

2. Waituna-type lagoons

Waituna-type lagoons are lacustrine hydrosystems occurring as large, shallow (mean depth 1 to 2 m) coastal lagoons, enclosed by a coarse clastic barrier or barrier beach and situated on wave-dominated high-energy coasts. Their waterbodies are typically fresh, fed by small streams, with brackish pockets. Drainage to the sea is generally via barrier percolation since their most frequent state is closed to the sea. Short-lived openings occur when water levels build a sufficient lagoon hydraulic head to induce a barrier breach. Sustained openings to the sea are rare unless mechanically opened. Two subclasses are recognised: 2A coastal plain depressions (e.g. Te Waihora Lake Ellesmere) and 2B valley basins (e.g. Te Roto o Wairewa Lake Forsyth) (both in central Canterbury).

For waituna-type lagoons, the overall responses to climate changes and SLR are likely to be pronounced, including shifts in the balance between river, tide and wave processes, affecting water quality and potentially triggering shifts for vulnerable lagoons into other system types.

Climate and wave climate changes, and SLR have the potential to decrease barrier percolation and restrict outlet drainage, leading to greater inundation of hinterland supratidal areas, barrier roll back, and erosion. If not balanced by increased sediment from longshore transport, these processes can lead to barrier breaching and breakup, transitioning waituna (2A) into estuarine (class 7) and/or embayment (class 11) systems. Barrier erosion and breaching processes have seen waituna lost in the past (e.g. Waimataitai, south Canterbury, Kirk and Lauder, 2000). Over Holocene timescales, waituna also have transitioned between non-estuarine, estuarine and embayment classes, with river avulsions and tsunamis (e.g. Norman, 2016).

Where waituna (2A) are fed by local streams and small rivers that experience reduced freshwater inflows in areas with drier climates, such as in eastern NZ plains and foothill catchments, this will lead to increased water residence times and longer-lived brackish conditions, water quality degradation and algal blooms. Water quality degradation is already common in many NZ waituna, due to the combination of catchment use intensification over recent decades with the long water residence times of these systems (Tables 5.2 and 5.3 in Hume et al., 2016). Alternatively, where waituna are fed by catchments projected to experience increased rainfalls, such as in Southland, increased inundation around the landward margins could allow natural barrier breach regimes to be maintained but may be undesirable to surrounding land users, leading to pressure on councils to increase mechanical openings. Intolerance of inundation around the landward margins could lead to shoreline protection works and ecosystem squeeze, while increased frequency of openings may prove difficult to maintain in the face of changing wave climates, and/or may accelerate hydrosystem flips into estuarine (7) or embayment (11) systems. Waituna 2B will be less prone to coastal inundation, given their valley basin morphometry. These systems may become either more or less connected to the ocean depending on the unfolding balance between SLR and coastal erosion/accretion with changes in longshore sediment transport.

3. Hāpua-type lagoons

Hāpua-type lagoons are riverine hydrosystems occurring as narrow, elongate and shallow (mean depth ~2 m) river mouth lagoons, enclosed by mixed sand gravel barrier beaches formed by strong longshore sediment transport. They occur on wave-dominated coasts, with micro- to meso-tidal ranges, typically with cliff backshores. River flow is seaward except just after large floods breach or widen outlets. They experience tidal backwater effects. Their outlets can migrate kilometres along the shoreline over days to weeks. Four subclasses are recognised: 3A occurring at the mouths of large braided rivers with alpine source areas (e.g. Rakaia rivermouth); 3B at the mouths of hill rivers (e.g. Ashburton rivermouth); 3C at the mouths of streams or small rivers (e.g. Opihi rivermouth); 3D on coasts where wave and tide dominance switches over time (e.g. Ashley rivermouth) (all in Canterbury).

For hāpua-type lagoons, the overall direct effects of SLR will likely be minor compared to current freshwater related pressures, though climate changes affecting catchment water balances could significantly compound current pressures. We will likely see changes in lagoon and barrier beach dimensions, water quality and ecosystem degradation, and increased pressure for management interventions.

In general, hāpua are not thought to be particularly vulnerable to SLR and coastal erosion processes alone under natural conditions, since these lagoons have persisted through Holocene SLRs and shoreline transgressions via parallel lagoon backshore retreat (i.e. via natural chronic erosion (Kirk and Lauder, 2000)). However, over the last few decades pronounced changes in many Canterbury hāpua indicate that these hydrosystems will be very sensitive to river flow changes from altered climates and any associated changes in freshwater use, as well as to effects from mechanical openings and structures (Hart, 2007; 2009; Creed, 2014; McHaffie, 2010).

Altered wave climates and stronger longshore transport, combined with lower river base flows due to drier climates and/or increased water abstractions, can lead to barrier strengthening (increased width and stability) in hāpua 3A to 3C. This can lead to more extensive and frequent inundation of low-lying margins during floods, since larger flows will be required to induce barrier breaches. More intense storms could induce more frequent barrier beach wave overtopping, flooding of lagoon margins and larger storm breaches (Hart, 2007). With projected reductions in plains rainfall in eastern NZ, lagoon closure could also become frequent and prolonged in hāpua 3B and 3C, with consequent reductions in lagoon flushing, water quality degradation and increases in algal blooms (Creed, 2014). Drier climates and increased freshwater use could see lower river flows at levels below peak floods, leading to lagoon shrinkage where subaerial and fluvial processes are less effective in eroding lagoon backshores, or where artificial openings are maintained to reduce hinterland inundation.

4. Beach stream

Beach streams are small shallow riverine hydrosystems that flow over a sand or mixed sand and gravel beach face. Drainage to the sea occurs for most of the time, except during drought conditions and/or when waves build a beach berm to close the outlet, so that water percolates through the beach face to the sea. There is no tidal inflow, except during storm events coupled with high tides. Five subclasses are recognised on the basis of the nature of the path the stream takes to the sea namely: 4A hillside stream (e.g. Heaphy Stream, West Coast SI); 4B damp sand plain stream (e.g. Granity Stream, West Coast SI); 4C stream with pond (e.g. Piha Stream, Auckland west coast); 4D stream with ribbon lagoon (e.g. Patten Stream, West Coast SI); 4E intermittent stream with ribbon lagoon (e.g. Shearer Swamp, West Coast, SI).

For beach streams, the overall responses to climate changes and SLR will vary greatly between subclasses, from very minor loss and landward migration of coastal fringes (4A) to complete losses with inundation, erosion and transgression (4D). River flood event increases could see breaching of lagoon barriers and streams taking a more direct path to the sea.

The effects of climate changes and SLR will be quite different for each beach stream subclass, with topography being a key determinant of responses in these systems. Minor effects will occur in subtypes situated on steep terrain while major effects will occur in those situated on flat, narrow, low-lying plains. The least affected will be 4A hillside streams, which discharge to the sea via a short, direct path over the beach. By contrast, systems that discharge to the sea over low-lying coastal plains (4B to 4E) could have their lower reaches inundated by SLR or be forced into landward retreat and squeezed against high ground, unless the plain is able to build higher via sediment supplied by stream and wave processes. SLR could also see a reduction in the drainage and flow capacity of systems and, in areas where river flows are reduced, the outlets to the sea might close more frequently, perhaps necessitating more mechanical openings to address flooding and water quality issues. Under SLR seawater will enter the mouths of beach streams more frequently during storm events. Beach streams 4B to 4D are likely to be sensitive to river flow changes from altered climates and, in particular, to any associated increase in freshwater inflow events and to effects from artificial openings to mitigate flooding. In extreme cases, 4D streams with ribbon lagoons fed by river flow may breach more regularly compared to 4E systems, which are buffered from floods by their connection to wetland drainage.

5. Freshwater river mouth

Freshwater river mouths are riverine hydrosystems that occur where river flow is large enough to cut a permanent subtidal channel through the shoreline and beach to the sea. The river channel gradient is steep enough to prevent tidal ingress, except at times of storm tides. While river flow dominates the hydrodynamics, there can be a tidal backwater effect. River mouths can discharge large amounts of sand and gravel to the sea and build a coastal plain over geological time. Three subclasses are recognised on the basis of the nature of the mouth namely: 5A unrestricted mouth (e.g. Waiau Toa Clarence River, Canterbury); 5B deltaic mouth (e.g. Tapu, Coromandel); 5C barrier beach enclosed mouth (e.g. Paringa River, West Coast SI).

For freshwater river mouths, the expected responses to climate changes and SLR will be minor overall, and dominated by changes in response to climate shifts, in particular those that alter the flow regime.

It is anticipated that there will be little overall effect from SLR on these systems. While SLR may enhance erosion of the shoreline where Holocene transgression is already occurring (e.g. Waiau Toa Clarence River mouth), this effect could be offset by any increase in river flows and sediment input. An increase in sea level could result in greater backwater effects in the rivers overall as well as for short periods during storms, resulting in flooding of adjacent low-lying land.

6. Tidal river mouth

Tidal river mouths are estuarine hydrosystems occurring as elongate, narrow and shallow (a few metres deep) basins. They occur where river and tidal flow are large and persistent enough to maintain a permanent subtidal channel through the shoreline/beach to the sea. River inputs to the system during a tidal cycle represent a significant proportion of the basin's total volume and exceeds tidal input to the system. Hydrosystem-scale hydrodynamic processes are dominated by river flows and the systems are well flushed. River floods can expel all the seawater from the system for days at a time. A salt wedge develops in deeper systems. Seawater can intrude kilometres upstream in systems occurring on low-gradient coastal plains. Wind-generated mixing and wave-driven resuspension are minor as wind fetch and waves are small and depths are largely too great for significant bed stress to be produced. Thus, sediments inside the waterbody tend to be muddy except in areas of high tidal flows. Five subclasses are recognised: 6A unrestricted mouth (e.g. Waihou River River, Waikato); 6B spit enclosed (e.g. Whanganui River, Taranaki); 6C barrier beach enclosed (e.g. Hokitika River, West Coast SI); 6D intermittent with ribbon lagoon (e.g. New River, Greymouth); 6E deltaic (e.g. Motueka River, Tasman Bay).

For tidal river mouths, the expected responses to climate changes and SLR will vary with subclass and could be significant.

The larger deeper systems that can extend kilometres inland (6A, 6B and 6C) are likely to see tidal intrusion and backwater effects extending further inland as sea levels rise, potentially threatening freshwater water supply intakes that are located further upstream, increasing flooding of low-lying coastal plain areas adjacent to the river, and a redistribution of ecological facies upstream accompanying the change in water level and salinity regime. Tidal river mouths enclosed by narrow sandy spits and gravelly barriers (6B and 6C) may experience an increased frequency of wave overwash events during storms. Small shallow systems such as 6D intermittent types, which today are particularly sensitive to changes in river flow and mechanical openings, are likely to experience an increase in barrier breaching events.

7. Tidal lagoon

Tidal lagoons are estuarine hydrosystems of shallow mean depth (1 to 3 m), with circular to elongate basins and simple (not dendritic) shorelines, and having extensive intertidal area. The narrow inlet is constricted by a wide spit or sand barrier. Strong tidal currents flow at the mouth where ebb and flood tidal deltas occur. Tidal inflow makes up a large proportion of total volume of water in the system and river inputs are correspondingly small. Lagoon salinities are close to that of the sea. River flows can dominate the hydrodynamics for short periods during floods. Storm tides can back up outflows causing low-lying land around the lagoon margins to be flooded. Two subclasses are recognised: 7A permanently open (e.g. Blueskin Bay, Otago) and 7B intermittently closed that become eutrophic when closed to the sea (e.g. Hoopers Inlet, Otago).

For tidal lagoons, the expected responses will mostly result from SLR. We may see progressive flooding of the low-lying margins by the sea, unless inhibited by structures or other processes, and potentially coastal squeeze in some systems while others will close more frequently due to reduced drainage, with consequent increases in eutrophication.

Effects from climate changes and SLR in these systems will mostly result from SLR, as freshwater flow to these systems is small compared to tidal exchanges. Lagoon intertidal areas will deepen unless offset by sedimentation and there will be progressive flooding of their low-lying margins unless this is inhibited by stopbanks or other structures, in which case there will be a decrease in intertidal area and coastal squeeze. The effect will be most pronounced in locations where the tidal range is small compared to the relative SLR. There is likely to be increased flooding of lagoon margins during storms, as incoming tides and elevated coastal water levels back-up outflows.

In larger, wider, and more open examples of this hydrosystem type, higher water levels will allow waves to attack soft shorelines for longer periods at high tidal stages, increasing the shoreline erosion rates. In contrast, 7B intermittently closed systems will close more frequently as SLR inhibits drainage, resulting in more eutrophic events. There is likely to be some landward migration of ecological facies (e.g. mangrove and saltmarsh) as SLR submerges present-day intertidal areas. An increased frequency of rainfall and runoff events in some regions could lead to more frequent smothering of sandy substrate benthic communities with muddy sediment inputs (see 'Estuaries and lowland brackish habitats', p55). At the entrances to barrier enclosed systems on sandy coasts, larger tidal prisms may increase the capture of longshore transport, resulting in a build-up of sand in the tidal delta sand bodies and consequent erosion of adjacent open coast beaches (Hicks and Hume, 1996). Low elevation sandy spits and barriers may experience an increased frequency of wave overwash and breach events during storms.

8. Shallow drowned valley

Shallow drowned valleys are estuarine/marine hydrosystems of shallow mean depth (<5 m) having complex dendritic shorelines with narrow arms leading off a main central basin or channel. They range in size from small tidal creeks to large harbours and have extensive intertidal flats. Hydrodynamics are dominated by tidal processes. Their mouths are permanently open, being constricted by hard headlands or substantial barriers. Flood and ebb tidal sandy deltas are present at the mouths on high wave energy, littoral drift shores (e.g. Raglan Harbour) but absent on zero-drift shores (e.g. Waitemata Harbour). These hydrosystems are significantly infilled with sediment, being sandy at the mouth and muddy in the headwaters where narrow intertidal tidal creeks occur (e.g. Paremoremo Creek, Waitemata Harbour).

For shallow drowned valleys, the expected responses to climate changes and SLR are likely to be significant overall, particularly in relation to changing climates. Adjustments will occur both around the edges and in central basin areas.

Shallow drowned valleys will see increased flooding of low lying coastal margins accompanying SLR, unless held back by engineering structures, and potentially increased depth, which may partially but not completely offset current and future sedimentation. Today the tidal creeks are scoured by increased flood flows from catchment urbanisation, and this will likely be exacerbated by climate change induced increases in rainfall intensities. In most systems the resultant increases in mud delivered to their wider basin areas will only partially offset SLR, meaning most systems will deepen overall. Channel dredging may need to increase though, to offset channel infilling and maintain vessel drafts. In larger, wider and more open systems, higher water levels will see greater wave attack on soft shorelines at high tidal stages, increasing shoreline erosion. This may, in turn, raise coastal erosion concerns for development on low-lying coastal terraces as well as some loss of soft shoreline amenity. SLR induced intertidal area losses will cause some redistribution of ecological facies (e.g. salt marsh and mangrove distribution may move landwards). Extensive landward transgressions will be prevented where margins include naturally steep valley sides or the artificial shoreline hardening of stopbanks and reclamations, resulting in coastal squeeze.

9. Deep drowned valley

Deep drowned valleys are estuarine/marine hydrosystems, typically large and deep (mean depth 10 to 30 m). Formed by the partial submergence of unglaciated river valleys they have a planform inherited from the flooded valley. Typically, they have a straight planform without significant branches, but they can be dendritic. In the Marlborough Sounds and Wellington Harbour there are islands which are the summits of partly submerged hills. The size of the valleys seems large for the size of the rivers currently entering the system. They are permanently open to sea and mostly subtidal. Both tidal and river inputs are small relative to their basin volumes. Circulation is forced by density currents and stratification is common. Wind and tide modify the circulation at times but are not responsible for the mean circulation over extended periods of time. These systems differ from shallow drowned valleys in that they are deeper, lack sand deltas at the mouth, have steeper margins and far less intertidal area, and their hydrodynamics are less tidally dominated. Examples include: Firth of Thames; Wellington Harbour; and Akaroa Harbour.

For deep drowned valleys, the expected responses to climate changes and SLR are expected to be minor overall, and edge focussed.

Changes in rainfall and tidal processes associated with climate changes and SLR are unlikely to affect the hydrodynamics of these hydrosystems, which are largely controlled by their deep basins and large total water volumes. However rising sea levels will allow waves to attack any soft margins for longer periods of time at high tidal stages, increasing shoreline erosion. This may, in turn, increase coastal erosion hazards for poorly sited developments in coastal areas, with potential losses of shoreline amenity and increases in pressure for management interventions. Rising sea levels will also see gradual reductions in habitat in smaller headwater intertidal areas from coastal squeeze, unless offset by river derived sedimentation. Deep drowned valleys with extensive low-lying coastal plains (e.g. Miranda coast in the Firth of Thames) are likely to experience more frequent coastal inundation of the plains, initially during storms with eventually total inundation. Overall, the effects in these hydrosystems will be minor and focussed around the edges.

10. Fjord

Fjords are estuarine/marine hydrosystems comprising long, narrow and very deep (70 to 140 m average) U-shaped basins with steep sides or cliffs, formed in glacial valleys flooded by Holocene SLR. Fjord basins are largely subtidal, with only very small headwater intertidal areas. Former terminal moraines form sills at the mouth and along the length of these systems. Both river and tidal inputs are very small compared to total basin water volumes. Water movement near the surface is controlled primarily by thermohaline forcing, due to large density differences between outflowing river-derived freshwater on the surface and inflowing seawater below. Wind-driven circulation dominates at times but is not responsible for the mean circulation over extended periods. Consequently, these systems are characterised by poor flushing, particularly in more complex-shaped (multiple arm) systems. The very deep basin and partitioning by sills means that flushing takes place in a relatively thin layer of freshwater, which moves over the top of a 'quiescent zone' of seawater. The substrate is generally fine sand or mud as the catchments are forested and resuspension by wind waves is minimal in these very deep basins. Fjords are restricted to Fiordland, with examples including: Charles Sound, Te Awa o Tū/Thompson/Doubtful Sound, Bligh Sound and Milford Sound.

For fjords, the expected responses to climate changes and SLR will be minor overall and focussed on erosion and habitat changes around the edges. Increases in ocean acidification and temperatures have the potential to strongly affect fjord ecology.

Changes in rainfall and tidal reach associated with climate changes and SLR are unlikely to affect the hydrodynamics of these hydrosystems, since circulation is largely a function of their very deep, steep-sided basins and large total water volumes. However, SLR may allow greater wave attack and localised erosion of soft shores and pocket beaches in their upper reaches. SLR will also see gradual intertidal habitat reductions in fjord headwaters from coastal squeeze, with river derived sedimentation unlikely to offset this process in these steep-terrain systems. More significantly, ocean acidification and temperature shifts could affect fjord ecology, alone and in combination with invasive species, with flow-on effects for tourism, the major economic activity in NZ's fjords. Overall fjord responses to climate changes and sea level rise will be minor in terms of geomorphology but potentially significant with regard to ecology and management challenges.

11. Coastal embayment

Coastal embayments are marine hydrosystems, occurring on low littoral drift shores as an indentation in the shoreline with a wide entrance, and bounded by rocky headlands. Their waterbodies are circular to elongate in planform, shallow to medium depth (4 to 8 m), and mostly sub-tidal. These pocket beaches contain small sandy dunes or shelly ridge systems above high tide, and small intertidal areas in the headwaters. Hydrodynamic processes are dominated mostly by tides as the enclosing headlands provide for only a narrow sector of wave entry. Coastal embayments differ from shallow drowned valleys in that they are largely subtidal, with their wider mouths allowing a greater degree of wave forcing. Examples include: Taemaro Bay and Matai Bay (Northland); and Te Matuku Bay (Waiheke Island).

For coastal embayments, the expected responses to climate changes and SLR are likely to be minor and to include intertidal habitat losses in their upper reaches, and increased shoreline rotation and/or erosion.

SLR in these hydrosystems is likely to see gradual reductions in intertidal habitat via coastal squeeze and potential increases in shoreline erosion rates, though net sediment losses are likely to be small as deposits are contained between headlands. These systems will be partially protected from changes in mean or storm wave directions, since wave energy can only enter these bays from a narrow sector, although planform shoreline rotation may occur as sand shifts from one end to another. Freshwater inflows into coastal embayments may alter with climate changes that affect rainfall or catchment aridity, but given their small inflows from streams, such changes are unlikely to have any substantial effects on the hydrodynamics and sedimentation in these hydrosystems. Overall, the effects will be minor both in relation to climate changes and SLR.

Conclusions

Climate changes and SLR have the potential to alter the primary drivers of coastal hydrosystem processes, namely fluvial inputs, tidal and wave processes, and to a lesser extent rainfall and longshore sediment transport (see Table 1). Resultant responses in these interface systems will be small or large depending on the degree to which their driver balance is altered, as well as on the nature of direct and indirect human responses.

In terms of SLR, effects will be most significant in hydrosystem classes where marine forcings are a significant portion of their total water volumes and flows. These effects will vary and may include the deepening of the channels and basins, and intertidal habitat migration and/or losses (with some offsetting via sedimentation, and some increased losses due to natural or human induced coastal squeeze). Comparatively minor adjustments to SLR are expected around the edges of systems where their total water volume is large compared to fluvial and tidal inputs, including deep drowned valleys, fjords and coastal embayments (classes 9, 10 and 11).

Images 1 to 11: Examples of the 11 different types of NZ coastal hydrosystem identified in Hume et al. (2016).

(1) Damp sand plain lake, Manukau North Head (Doug Ramsay, n.d.);

(2) Waituna-type lagoon, Te Waihora/Lake Ellesmere, Canterbury (Google/Landsat/Copernicus, 2016);

(3) hāpua-type lagoon, Hakatere/Ashburton River, Canterbury (Google/Maxar Technologies/CNES/Airbus, 2016);

(4) Beach stream, Piha Stream, Auckland (Google/Maxar Technologies, 2015);

(5) Freshwater river mouth, Waiau Toa/Clarence River, Canterbury (Google/ Maxar Technologies, 2020);

(6) Tidal river mouth, Whakatne, Bay of Plenty (Google/Maxar Technologies, 2020);

(7) Tidal lagoon, Waiputai, Blueskin Bay, Otago (Google/Maxar Technologies, 2020);

(8) Shallow drowned valley, Mahurangi Harbour, Auckland (Google/Landsat/Copernicus/Maxar Technologies, 2020);

(9) Deep drowned valley, Akaroa, Canterbury (Google/ Copernicus/Maxar Technologies/CNES Airbus, 2020);

(10) Fjord, Te Awa o Tū/Thompson Sound, Southland (Google/ Landsat/Copernicus/Planet.com/Maxar Technologies, 2020);

(11) Coastal embayment, Taemaro Bay, Northland (Google/Maxar Technologies, 2020).

Responses to SLR will vary not only between coastal hydrosystem classes, but also as a result of regional differences in tidal range (Byun and Hart, 2020), wave energy ('The response of sandy coastal systems to changes associated with sea level rise', p25) and climate (MfE, 2017). For tidal river mouths (6) and tidal lagoons (7) effects will differ between regions, as will the importance of edge effects in deep drowned valleys (10) and coastal embayments (11). In contrast, damp sand plain lakes (1), freshwater river mouths (5) and fjords (10) are clustered according to similar tidal, wave and/or climate conditions, such that lessons from one system may be extrapolated across other systems of the same type.

Some hydrosystems are considered relatively robust in the face of SLR alone, but hypersensitive to the combined effects of climate changes and human influences. Hāpua (3), for example, have persisted through Holocene SLR but are experiencing significant and growing negative effects from river flow and freshwater use changes, mechanical openings and structures, pressures that will likely increase with climate changes unless managed via altered catchment and coastal use practices.

While some coastal hydrosystems will exhibit gradual ongoing effects from SRL and climate changes, others may switch geomorphic class subtype (e.g. hāpua 3, tidal river mouths 6, and tidal lagoons 7); flip into completely different types (e.g. waituna 2A); or disappear completely (e.g. damp sand plain lakes 1) once thresholds for change are reached.

Overall this review of the potential and likely responses of New Zealand coastal hydrosystems to climate changes and SLR underlines, not only the range of response types and rates but also, that catchment and coastal management practices can strongly influence responses across all system types. Numerous examples exist today where anthropogenic developments or interventions have produced physical process changes with undesirable hydrosystem effects. Key interventions include reclamations, stopbanks, shoreline hardening or re-contouring, mechanical openings, dredging, water extractions, spoil dumping, and mangrove removal. In many cases these have greater consequences for coastal hydrosystems than climate changes and SLR effects combined. They are also typically the most immediately modifiable component of hydrosystem influences.

There is a sensitive balance of processes operating in coastal hydrosystems, combined with uncertainties in the trajectories of climate changes and sea level rises, and in how systems are responding. This means that robust monitoring of systems is needed to feed into adaptive management policies and practices (e.g. Tait and Pierce, 2019) and to minimise adverse effects from SLR and climate changes. Few New Zealand coastal hydrosystems are currently subject to robust monitoring and adaptive management regimes and further research is needed to improve management outcomes. Thus, a significant shift in regional and national management approaches to coasts and catchments is urgently needed to safeguard New Zealand's diverse coastal hydrosystems.

References

Byun, D-S, and Hart, DE (2020). A monthly tidal envelope classification for semidiurnal regimes in terms of the relative proportions of the S2, N2, and M2 constituents. *Ocean Science* 16(4), 965-977.

Creed, S (2014). *A classification of small hapua-type river mouths on the mixed sand and gravel coasts of Canterbury, New Zealand*. University of Canterbury Geography Honours dissertation.

Hart, DE (2007). River-mouth lagoon dynamics on mixed sand and gravel barrier coasts. *JCR* SI50, 927-931.

Hart, DE (2009). River mouth lagoon science and management. In: A Williams and A Micallef (eds.), *Beach management: Principles and practice* (1st edn.), London: Earthscan, 273-286.

Hart, DE, et al. (2020). Earthquakes, coasts… and climate change? Multi-hazard opportunities, challenges and approaches for coastal cities. *JCR* SI95, 819-823.

Hicks, DM, and Hume, TM (1996). Morphology and size of ebb tidal deltas at natural inlets on open-sea and pocket bay coasts, North Island, New Zealand. *JCR* 12, 47–63.

Hume, T, et al. (2016). *A classification of New Zealand's coastal hydrosystems*. NIWA Client report HAM2016-062, for the Ministry for the Environment, 120p, www.mfe.govt.nz/publications/marine/classification-of-new-zealands-coastal-hydrosystems.

Kirk RM, and Lauder, GA (2000). *Significant coastal lagoon systems in the South Island, New Zealand*. Department of Conservation, Wellington.

McHaffie, N (2010). *A GIS based analysis of changes in the Rakaia Hapua, Canterbury*. University of Canterbury Geography Honours dissertation.

MFE (2017). *Coastal hazards and climate change: Guidance for local government*, 279p. www.mfe.govt.nz/climate-change/technical-guidance/guidance-local-governmentpreparing-climate-change

Norman, M (2016). *The evolution and environmental history of Wainono Lagoon, New Zealand*. MSc thesis (GEOG), University of Canterbury, http://tinyurl.com/y6q8t96s.

Oppenheimer, M, et al. (2019). Sea level rise and implications for low-lying Islands, coasts and communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, H-O Pörtner, et al. (eds.), in press.

Tait, A, and Pearce, P (2019). *Impacts and implications of climate change on Waituna Lagoon, Southland*. Science for Conservation Series 335, Department of Conservation, Wellington, 26p.